NAPL - North Pacific Acoustic Laboratory

PI James A. Mercer
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-1361 fax: (206) 543-6785 email: mercer@apl.washington.edu

CO-PI Rex Andrew
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-1250 fax: (206) 543-6785 email: rex@apl.washington.edu

CO-PI Bruce Howe
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-9141 fax: (206) 543-6785 email: howe@apl.washington.edu

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.

2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.

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14. ABSTRACT
The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

15. SUBJECT TERMS

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3. To develop theory and models to explain acoustic energy that propagates into the geometric shadow zone beneath deep caustics (shadow-zone arrivals) as measured with the NPAL network of bottom-mounted SOSUS receivers, the LOAPEX vertical line array, and ocean bottom seismometers.

4. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.

5. To elucidate the roles of internal waves, ocean spice, and internal tides in causing fluctuations in acoustic receptions.

6. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.

APPROACH

NPAL employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The NPAL network, operated and maintained by APL-UW, provides an actual laboratory for real-time propagation measurements at a selection of basin-scale distances, the capability to test various transmission signals, and ambient noise measurements at various locations in the Pacific Ocean. The network consists of an acoustic source near the Island of Kauai, HI controlled from Seattle, WA, the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. The National Marine Fisheries Service Letter of Authorization for the acoustic source expired last year; hence transmissions have been suspended until the permit is renewed. Figure 1 illustrates the locations of acoustic hydrophone arrays in the NPAL network.

The second avenue includes highly focused, relatively short-term experiments.
The most recent NPAL experimental effort actually consisted of three coordinated experiments. APL-UW conducted the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), SIO was responsible for the SPICEX experiment, and MIT and OASIS performed the Basin Acoustic Seamount EXperiment (BASSEX).

The approach of NPAL also includes collaboration with a number of researchers from several other institutions who provide further analysis of NPAL experimental data and theoretical development. The collaboration is enhanced by holding yearly NPAL conferences usually near Seattle or San Diego. This year's meeting was hosted by APL-UW in Leavenworth, WA.

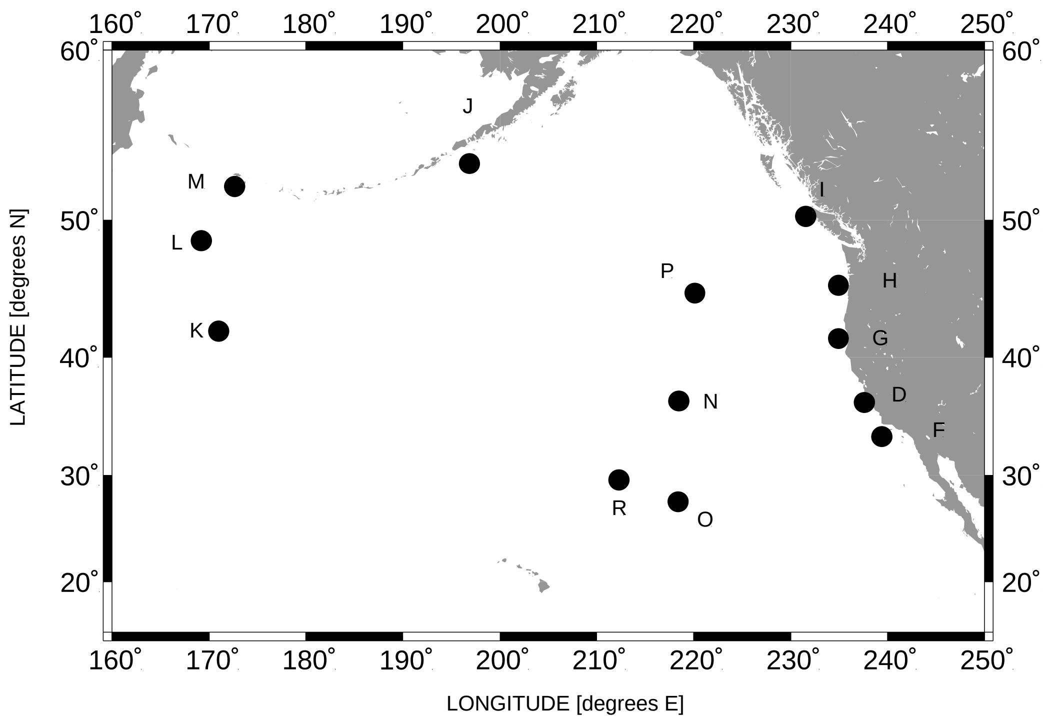

Figure 1. The NPAL hydrophone array network. The locations of arrays identified by the letters R, D, E, and F are exact. The other locations are notional. The entire network is controlled and monitored from APL-UW.

WORK COMPLETED

A paper describing the NPAL Long-range Ocean Acoustic Propagation EXperiment (LOAPEX) was prepared and submitted to the IEEE Journal of Oceanic Engineering [1]. In addition to providing preliminary results, it is expected that the paper will provide a handy reference for authors publishing additional results from this experiment.

In order to assist NPAL researchers at other institutions we developed and made available a “Doppler Toolkit,” a collection of C++ classes that can be assembled to estimate the time-base dilation between a moving transmitter and receiver, both being specified by tabulated solutions of their 4-dimensional position *x(t)*, *y(t)* and *z(t)*. The toolkit also contains a multi-channel implementation of a re-sampling “sinc” interpolation filter that can “de-Dopplerize” raw acoustic data. A description of the de-Dopplerizing algorithm has been included in a paper submitted to the IEEE Journal of Oceanic Engineering [2].

In February 2007 APL-UW hosted many of the NPAL participants in a “Tiger Team” meeting to define the next major NPAL experimental effort. The results of this meeting [3] have been adopted and form the straw man concept for an experiment to be conducted in the Philippine Sea. In May 2007 APL-UW hosted the 10th NPAL Workshop attended by NPAL sponsors and investigators from across the country. Twenty-seven papers were presented, most of which were related to the LOAPEX experiment.

An APL/UW Technical Memo [4] summarizing the CTD and sound-speed measurements made on the "Internal Wave" cruises of 1998 and 1999 was finalized and published. An electronic copy of the memo and all the existing raw and processed data products were assembled onto a master CD for further distribution.

Transmissions in 2006 from the Kauai acoustic source, operated by APL-UW, were received on an array supported by another ONR program. The data were provided to APL-UW in 2007 for processing because of the unique code used in the transmissions. The data were processed and the results forwarded to ONR Code 321OA.

At the request of Naval Ocean Processing Facility, Whidbey Island, NPAL receiver/processor hardware was re-configured to allow modifications to the Navy's distribution of data to "alternate users."

RESULTS

Ambient Noise. As part of our NPAL charter, we have been conducting a long-term program to study omni-directional ambient sound autospectra. Under this program (which actually began in 1993-1994 before NPAL), three-minute autospectra are collected autonomously every 5-6 minutes around the clock for all receiving arrays in Figure 1. In 2002 we published a paper [5] comparing data collected by Wenz [6] at array "D" (Figure 1) between 1963 and 1965 with our data collected at array "D" from 1994 to 2001. The results indicated a 10 dB increase in ambient noise in the band between 20 and 80 Hz. Comparisons at the other sites were not made because of our lack of knowledge about the absolute calibrations for these sites. During the past several years, this program has been a low priority effort, and chiefly involved data collection and cataloguing.

This year a serious effort was directed towards updating and upgrading the data archive. The primary goal was to identify a reasonable calibration for each site, and thereby lay a solid foundation for future dataset analysis. These calibrations are based upon knowledge of the transfer function between the in-water acoustic field and the voltage digitized by the APL-UW measurement system. The transfer function elements include the hydrophone and cable properties, shore-side navy hardware including amplifiers and filters, and the APL-UW measurement system. By a number of methods a great deal has now been discovered about the navy hardware and it is now possible to extend the comparisons to additional array sites [7].

Using the corrected datasets from sites D, F, G, and H, we have been able to investigate the trend in low-frequency sound since 1994 [8&9]. Examining synthesized one-third octave levels, we find that the vocalizations of fin and blue whales make the dominant contribution at 16 and 20 Hz virtually year round, particularly at the southern sites. At higher frequencies, the contribution from distant shipping becomes significant, although sometimes only seasonally. We estimated a least-squares linear trend to this distant shipping contribution at 25, 31, 40 and 50 Hz. Figure 2 shows the trend solutions at 31 Hz. We see evidence of a statistically significant but smaller increase in ambient noise since 1994 at sites D and F, but not at sites G and H. Figure 2 also shows a comparison between our data and the (point) measurements reported by Wenz for the same sites over 1963-1965. The results at sites F, G, and H corroborate the increase of about 10 dB between the 1960's and the 1990's reported for site D [5].

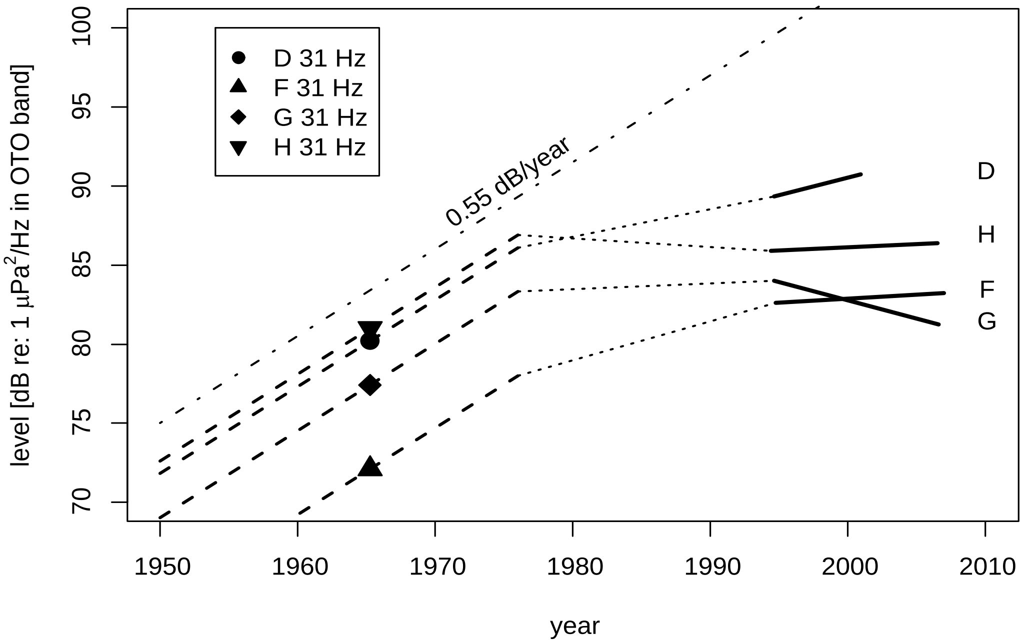

Figure 2. Comparison of APL-UW ambient noise measurements from 1994 to present for 4 sites (D, F, G, and H) versus point measurements in the mid 1960's from the same site. All data are for 31 Hz.

Kauai Acoustic Source Transmissions. Transmissions from the Kauai acoustic source were terminated in September 2006. In accordance with the Letter of Authorization, we were permitted to transmit with a higher duty cycle (8%) for several days before the termination. During this time the transmission schedule was changed to one two-hour transmission on each day. An exception to this was that once a week we transmitted 6 twenty-minute specially coded transmissions for Mike Brown (Univ. of Miami). The two-hour transmissions consisted of 264 phase-coded M-sequences of 27.28 s duration. As a simple proxy for temporal coherence, we sequentially "stacked" (added) the received M-sequences together as if they had arrived at the same time. Since our usual processing output provides signal-to-noise ratio (SNR), the gain in SNR as each subsequent processed M-sequence was added to the previous ones provided an estimate of temporal coherence. Figure 3a shows the results of this process for receptions of one of the stronger multi-path arrivals at the array labeled "R" in Figure 1. The results for other receivers were quite similar. For comparison, an internal wave model developed by Frank Henyey (APL-UW) was used with a PE propagation code developed by Mike Wolfson (APL-UW) to simulate the measured data. A Garrett-Munk internal wave strength of 1.0 was used. These results are shown in Figure 3b where the values for the first twenty multi-path arrivals were used. Although the ordinate values are different for this plot, both plots suggest a coherence time of roughly 15-20 minutes with no decrease in coherence.

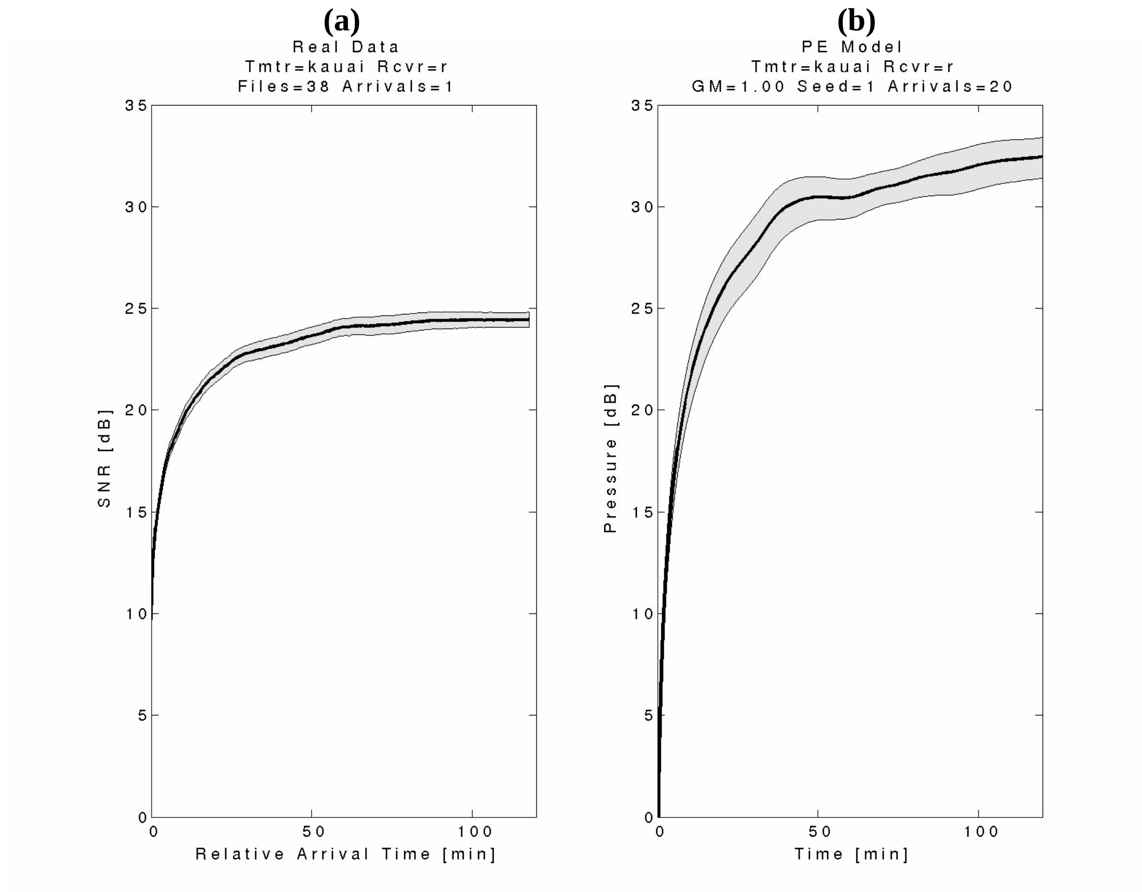

Figure 3. (a) This plot shows the mean and standard deviation of the signal-to-noise ratio for 38 receptions at site R of a single multi-path transmitted from the acoustic source near Kauai. Each transmission contained 264 M-sequences that were added together to form a proxy for coherence. (b) This plot shows the mean and standard deviation of simulated pressure at receiver R of twenty multi-paths transmitted from the Kauai acoustic source. Again, the simulated transmission contained 264 M-sequences. The simulation was based upon a PE propagation model that included internal waves with a Garrett-Munk strength of 1.0. In both cases the coherence time was about 15-20 minutes.

LOAPEX. A major focus of this year's work has been the analysis of data from the LOAPEX experiment. One of the goals of the LOAPEX experiment was to measure the first moment of the propagating acoustic field; i.e., the "mean field" [10], because it may provide insight into several quantities of fundamental interest: (1) the decay rate (with range) of the mean field may be related to the internal wave spectrum [11], and (2) the mean field might figure into a low-complexity approximation for select acoustic field second moments [12]. Assuming ergodicity, the mean field estimator is the arithmetic average. This is a coherent operation, and requires that all systematic causes of "wander" (i.e., jitter) be removed from the individual pulse records prior to averaging (because these would bias the result downward.) These systematic influences are (1) acoustic source motion, (2) receiver motion, and (3) tidal advection. Figure 4 illustrates the assets employed during LOAPEX and the experimental geometry.

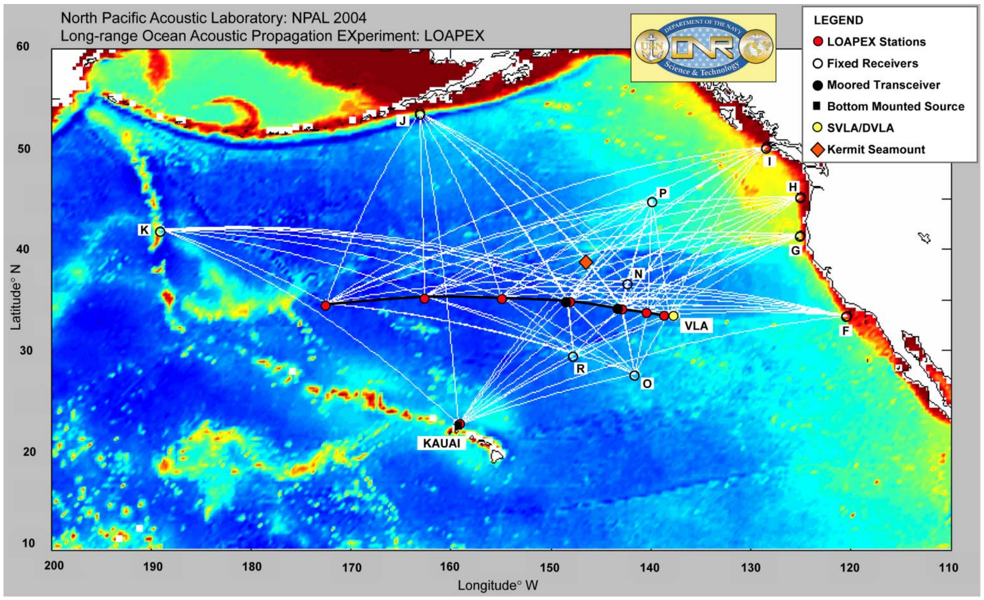

Figure 4. The LOAPEX geometry and assets. Seven red dots along the black cruise path indicate stations from which a low-frequency acoustic source was suspended at various depths from the R/V MELLVILLE. An eighth station was taken near the Kauai acoustic source. The open circles labeled with alphabetical letters represent permanent hydrophone arrays of the NPAL network used in LOAPEX. The red diamond locates the area of seamounts that were studied during BASSEX. The yellow dot shows the location of two vertical line arrays. Ocean bottom seismometers were also deployed near one of the vertical line arrays. The white lines indicate the geodetic paths between source locations and receivers.

The suspended acoustic source position was estimated using a novel scheme involving precision GPS measurements of the top of the electro-mechanical suspension cable, subsurface currents measured with the ship's ADCP, and a dynamical model of the cable itself. This analysis has been reported earlier in Michael Zarnetske's MS thesis [13] and in a paper submitted to the IEEE Journal of Oceanic Engineering [2]. This scheme is believed to have produced 3-D source position estimates accurate to within 1.5 m for all LOAPEX stations.

The yellow dot in Figure 4 represents the location of two vertical line arrays (VLAs) installed by the Scripps Institution of Oceanography (SIO). The arrays were separated by 5 km and one is referred to as the Shallow VLA (SVLA) and the other as the Deep VLA (DVLA). The VLAs were navigated by a transponder net installed and surveyed by SIO. The net was nominally interrogated once per hour: six hydrophones and the electronics module in each array segment were instrumented to capture the navigation signals. As reported last year, the middle section of the DVLA failed. In addition, some of the navigation tasks were not completed, resulting in gaps in the (otherwise) hourly 3-dimensional position records.

It proved remarkably easy to interpolate solutions when one or two or even three hourly solutions were missing. Interpolating through longer gaps, however, proved much more problematic. Unfortunately, the long gaps of missing data occurred precisely during LOAPEX transmission windows. During these windows, it frequently occurred that position data would be recorded on one of the three DVLA

segments, but not on the others. It therefore seemed profitable to develop a “coupled” solution for all the sensors in each segment and all segments in each array. This effort has been extremely tedious, but is just now proving profitable. Preliminary results [14] are indicating position errors of 2 to 3 meters for the DVLA hydrophone elements. This will allow estimates of coherency including the mean acoustic field.

Moving Ship Thermometry. During the LOAPEX experiment, acoustic transmissions from the eight ship stations were received on the hydrophone arrays shown in Figure 1. A Gauss-Markoff inverse solution [15] using this data has yielded a nearly synoptic sound-speed field for the basin. Figure 5 shows the sound-speed difference between the acoustic result and the starting field based on the World Ocean Atlas (WOA). The associated error estimates revealed a significant reduction in the a priori errors in portions of the field and illustrate the potential for moving ship thermometry. The results were presented at the December 2006 meeting of the Acoustical Society of America.

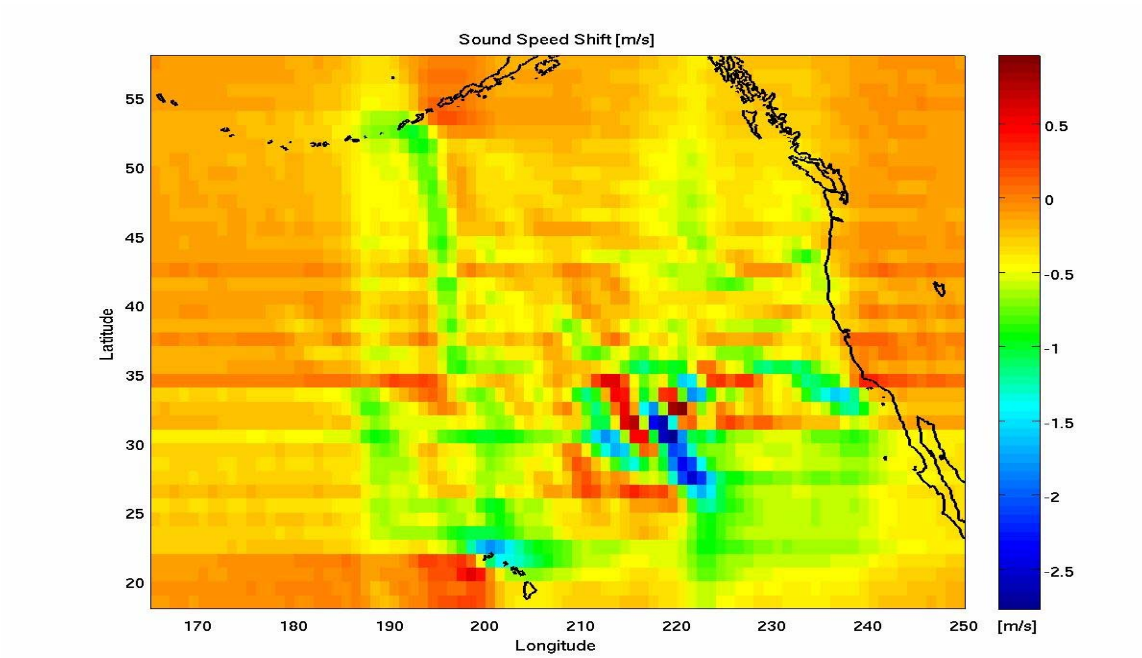

Figure 5. The difference between the acoustically determined sound speed and the World Ocean Atlas sound speed averaged in the upper 1000 m of the NE Pacific Ocean Basin. The result is significant for differences greater than 0.5 m/s. The color bar is in meters per second.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our

ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

RELATED PROJECTS

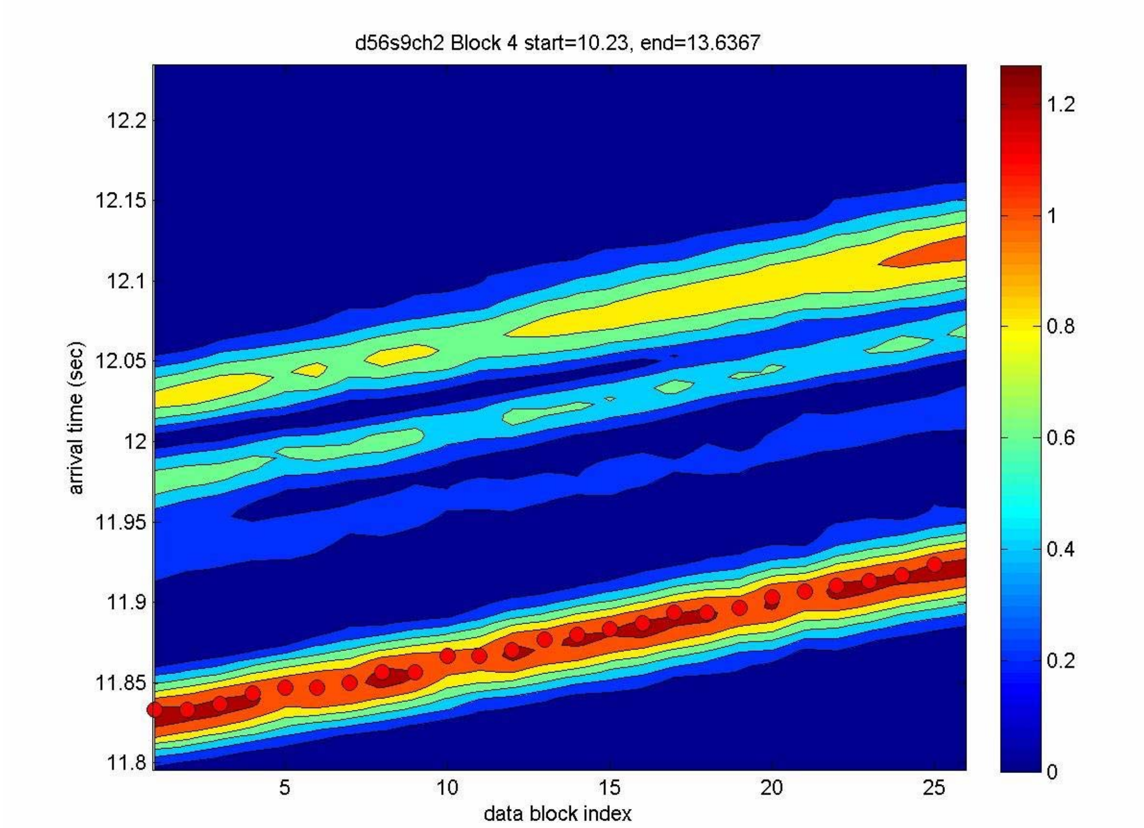

Figure 5. Coherently processed acoustic Seaglider data received from the Kauai acoustic source. The change in arrival time is consistent with the motion of the Seaglider.

In related work, data from the Kauai deployment of an acoustic Seaglider in September 2006, was analyzed. This glider with a hydrophone listened to the last transmissions of the Kauai NPAL/ATOC 75 Hz source out to a range of 200 km. Coherent processing of the M-sequence signals was possible (with 10 dB of gain) with the glider moving. In one particular data segment, the glider moved 136 m horizontally and 33 m vertically over a period of 12 minutes. Figure 5 shows the relative travel time increasing by 3.8 ms (5.5m) per 27.28 s M-sequence, equivalent to 0.204 m/s, consistent with measured Doppler shift and the estimated glider kinematics. While this work was funded by the ONR Acoustic Seaglider project, the results are relevant to the use of this tool in future NPAL and ocean acoustics experiments.

A large number of additional investigators are involved in ONR-supported research for the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), S. Flatté (UCSC), F. Henyey (APL-UW), V. Ostachev (NOAA/ETL), R. Stephen (WHOI), S. Tomsovic (Washington State), A. Voronovich

(NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), M. Wolfson (APL-UW), G. Zaslavsky (NY Univ.), and others.

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